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The impact of sensorimotor and cognitive capacity on the kinematic performance of instrumental activities of daily living across the lifespan

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Abstract

Background

With advancing adult age, sensorimotor and cognitive capacity (e.g., muscular strength) are declining and limitations in instrumental activities of daily living (iADL) are frequently reported. The translation of individual capacity to iADL performance represents a significant research object not only to better understand everyday life behavior but also to apply preventive measures in time. Due to the submaximal nature of iADL, we aimed to identify transition points, beyond which associations between capacity and performance appear, i.e., iADL stop to be submaximal.

Methods

A set of sensorimotor and cognitive capacity tests and kinematic analyses of hand movements in different complex kitchen tasks were conducted in a sample of 95 healthy adults with an age span of 18 to 93a. An iADL score was derived from the kinematics using a principal component analysis. Transition point segmented regression analyses were applied to examine the association of capacity and the iADL score.

Results

Most tests reacted to ageing and (negative) outlier frequencies in capacity and, to a weaker extent, in kinematics increased with advancing age. Transition points were identified in most tests and confirmed our hypothesis but were generally high. The best iADL performance was observed in persons between 42 and 58a despite decreased capacity.

Discussion

It appeared that iADL can be limited by impaired capacity, but profit from experience that can compensate capacity losses to a certain degree. The high transition points point towards the need for early interventions long before subtle alterations in iADL performance become subjectively observable.

Introduction

As people age, they frequently report impaired performance of instrumental activities of daily living (iADL) [Gaertner, 2019]. The underlying reasons, if taking actual performance into consideration as self-reports experience age-dependent bias [Kalisch, 2006], necessarily are to be found in the individual capacity [Newell, 1986], as tasks and environments of daily activities can be preserved over time. Capacity refers to the maximum achievable performance (a potential), e.g., in terms of muscular strength, information processing speed. iADL are often complex tasks [Gulde, 2017a] that, due to their

history of execution, are perceived as familiar [Gulde 2019]. Therefore, it can be assumed that reported (i.e., perceived) performance impairments are rather associated with health-related events (e.g., stroke [Penta, 2001] or arthritis [Wæhrens, 2012]) than with subtle, progressive declines in the natural history of ageing (which can simply lead to progressively avoiding a task that becomes too demanding [Schwerz de Lucena, 2021]). Still, clinical tests, such as the box and block test or grip strength measurements, are being used to predict ADL capabilities [McGee, 2003; Penta, 2001]. This raises several questions. First, when do iADL stop being submaximal [Gulde, 2017a; Gulde, 2019; Rice, 1998] in their demands, so that sensorimotor capacity is translated into performance declines during iADL? Second, do capacity declines account for the performance of a specific task or part of a task [Alonso, 2018; Gulde 2017b]? Third, which dimension of performance is impacted by reduced (in this case) sensorimotor capacity – what (content) is done or how (execution) it is done [Goldenberg, 2013; Gulde, 2017b]? Fourth, do (task-specific) skill and knowledge, as they can increase over time [Gulde, 2019], mask potential capacity-dependent declines of iADL performance? To put it short: At which level is capacity limiting iADL performance, are these limitations task- or action-specific, are both content and execution affected, and can limited capacity be compensated?

Here, we addressed the capacity-performance relation by examining the relationship between a set of sensorimotor, sensory, and cognitive tests and the kinematic iADL performance over a variety of kitchen-related tasks in a sample covering a wide adult age-span. While kinematic analyses do not examine task performance on a content level [Gulde, 2017b], they can quantify the quality of motor execution. They can further give hints concerning cognitive demands, as insecurities can be reflected by, i.a., hesitations in performance [Gulde, 2017a]. In the past, we were able to show the feasibility of kinematically analyzing the end-effectors (i.e., hands; the upper-limbs are most crucial for iADL execution [Oliveira, 2018]) with optoelectronic motion capturing in the laboratory as well as wearables (accelerometers & gyroscopes) in laboratory as well as daily life in ageing [Gulde, 2017a; Gulde, 2019], stroke [Gulde, 2017b; Gulde, 2024; Gulde, 2025], multiple sclerosis [Gulde, 2023; Gulde, 2025], and frailty [Schmidle, 2022]. Especially interesting was the observation that changes in capacity (i.a., grip strength) due to rehabilitation in stroke and multiple sclerosis translated into everyday life kinematics [Gulde, 2025]. Also, other groups have shown that kinematics are meaningful, objective, and sensitive indicators of task performance during stroke recovery, may it be in reaching tasks [Balasubramanian, 2012; Rohrer, 2002] or simple ADL [Alt-Murphy, 2013; Prange-Lasonder, 2021].

The used paradigm allowed to examine iADL performance in the light of age-related changes of sensorimotor and cognitive capacities, covering the potential points at which normal, age-related capacity changes can shift iADL past the submaximal-demands domain. As such relations can be strongly task-dependent, we used a set of tasks to make more general statements, and as we were exploring subtle changes, we only used non-failure trials and did not include content analyses (e.g., counting action errors). Last, we used common, time- and technology-robust tasks (e.g., preparing tea using a teabag) to avoid strong effects of cultural changes over time and task familiarity and execution frequency in mid-aged to elderly adults [Gulde, 2019]. Changes during early adulthood (e.g., by becoming

familiar with tasks), however, would be displayable, as no meaningful sensorimotor or cognitive declines or increases could be expected for this age range (considering submaximal task performance).

Taken together, the used paradigm allowed us to identify which dimension of capacity becomes relevant at which level for kinematic (how a task is executed) iADL performance over the lifespan.

Methods

Sample

The sample consisted of 95 healthy adults, aged from 18 to 93a (52a ± 21a). 58% (n = 55) of participants were female, 16% (n = 15) were left-handed based on self-report. The sex-specific age similarity was limited (t-test: p = 0.138, females 55a ± 21a, males 48a ± 21a). The body mass index (BMI) ranged from 17.3 to 39.4kg/m² (23.6kg/m² ±3.5kg/m²). Inclusion criterion was being 18a or older, exclusion criteria were neurological disorders, substance abuse, major depression, anxiety disorders, dementia, other psychiatric conditions, moderate or severe movement-restricting comorbidities affecting the upper extremities, such as impingement syndrome, arthritis, or stroke, and previous head injuries or traumatic brain injury. Recruitment took place primarily within the university setting, including students from sport and health-related disciplines, staff, and individuals connected to the academic environment. Additional participants were recruited in the Munich metropolitan area via flyers and through participants' networks. Further older adults were recruited from a private retirement residence that offers independent and assisted living, as well as a range of social and cultural programs. While educational attainment was not controlled for, measures of cognition were assessed. Furthermore, the academic setting and the characteristics of retirement residence suggest a homogenously high educational background. All subjects gave written informed consent to participate. The study was part of the TUM Innovation Network eXprt, ethical approval was given by the ethics committee of the Technical University of Munich (identifier: 2023-212-S-KH).

Procedure, Equipment, & Tests

After a screening, participants were asked to first execute different iADL, followed by set of capacity tests (the order was chosen to avoid carry-over effects of maximum performance tests and fatigue) in the TUM Living Lab (Fig. 1), a laboratory with an inbuilt kitchen and a 13-camera optoelectronic motion capturing system (Miqus M3, Qualisys AB, Gothenburg, Sweden), recording single passive-reflective markers in the center of the dorsum of both hands at 120Hz.

The screening covered self-reported anthropometrics and the six-item cognitive impairment test (6CIT; reporting current year (1), month (2) and time (4), recalling a postal address (3 & 7), counting backwards (5), naming the 12 months backwards (6)) [Katzmann, 1983]. The capacity test battery comprised of a simple reaction time test (average of 10 trials on a smartphone (Samsung Galaxy 2018a, Samsung Group, Suwon, South Korea) screen [Gulde, 2023]), the two-point discrimination task (minimal detectable

distance of two points on the fingertip) [Bell-Krotoski, 1993], a finger tapping task (using the whole upper-limb to tap with the index finger on a smartphone screen for 10s [Gulde, 2023]), isometric grip strength (using the best of three trials; Deyard EH101, Deyard Tech, China) [Volaklis, 2015], the box & block test [Mathiowetz, 1985], and the timed up and go test (with a distance of 2x3m and arm rests) [Browne, 2018]. The timed up and go test was included, as all kitchen tasks were executed standing and included movements along the kitchen plate. Side-specific tests were averaged across both hands. All tests, their domains, targets, and outcomes are listed in Table 1.

Participants executed four different iADL, being instructed to carry them out as naturally as possible (especially considering speed) [Gulde, 2017a; Gulde, 2017b; Gulde, 2019]. The tasks were to (1) empty a dishwasher filled with 9 plates (3 small plates, 3 big plates, 3 soup plates), 2 cups and 6 glasses, and 16 pieces (4 forks, 4 knives, 4 teaspoons, 4 tablespoons) of cutlery, to (2) toast two slices of bread (toast) and add spread and jam, to (3) boil coffee using a Bialetti moka pot and serve the coffee in an espresso cup with one sugar cube and to (4) prepare a cup of tea with one sugar cube and some milk. The set-ups were standardized but not adjusted to left-handedness (Fig. 2). Single passive-reflective markers of the motion capturing system were attached to the dorsum of the hands [Gulde, 2017a; Gulde, 2017b; Gulde, 2019] to record their position in time and space. Derived spatiotemporal data were transformed to a velocity magnitude via the Euclidean mean and resulting velocity time-series were smoothed using a 0.42s local regression filter (locally weighted non-parametric regression fitting using a 2nd order polynomial) [Gulde, 2018b]. Waiting periods, e.g., until the water was boiling in the tea making task, were defined as periods in which none of the hands moved (velocity magnitude < 0.05m/s) for at least 5s. All data processing was done in MATLAB (R2024b, The MathWorks Inc., Natick, MA).

Table 1
Tests, outcome measures, domains, and target dimensions of capacity tests and kinematic parameters

Domain	Test / Parameter	Abbrev.	Target	Outcome	Direction
Cognition	Six-item cognitive impairment test	6CIT	Memory	Error score	Lower is better
	Simple reaction time task	RT	Information processing speed	Average reaction time [ms]	Lower is better
Sensation	Two-point discrimination	2PDT	Sensory resolution	Detectable distance [mm]	Lower is better
Motor function	Finger tapping	TAP	Motor Speed	Frequency [Hz]	Higher is better
	Grip strength	GRIP	Muscular strength	Sex-specific z-score	Higher is better
	Box & block	BB	Manual dexterity	Transferred blocks per minute [1/min]	Higher is better
	Timed up & go	TUG	Ambulation & postural control	Speed [1/min]	Higher is better
ADL Kinematics	Trial duration	TD	Temporal volume	Average z-score over the four tasks	Lower is better
	Path length	PL	Spatial volume		Lower is better
	Relative activity	RA	Temporal fragmentation		Higher is better
	Mean peak velocity	MP	Movement speed		Higher is better
	Number of velocity peaks	NP	Spatial fragmentation		Lower is better
	Velocity-acceleration peaks ratio	VAPR	Movement smoothness		Higher is better
	Bimanual cooperation	BC	Temporal laterality		Higher is better
	Bimanual quotient	BQ	Volume laterality		Lower is better

Domain	Test / Parameter	Abbrev.	Target	Outcome	Direction
	Hand distance	DIST	Spatial centeredness		Lower is better
	ADL component score	ADL	Overall performance		Higher is better

Kinematic analysis

For each task, the following set of parameters was calculated and for each participant, an average z-score (over the tasks) was built. An overview of the parameters and their targets are listed in Table 1.

Trial duration is the total time to execute a task, excluding waiting periods, in [s], and a common performance marker [Reyes-Guzmán, 2014]. Longer trial durations have been linked to neurological impairment [Gulde, 2017b; Gulde 2018a; Huang, 2024; Pau, 2023; Schwarz, 2022] and ageing [Gulde, 2017a]. Path length is the trajectory length of both hands in [m] and represents the work volume. Longer trajectory lengths have been reported in neurological disease [Chen, 2021; Gulde, 2017b] and in ageing [Gulde, 2017a]. Relative activity is the relative amount of time in which at least one of the hands was exceeding a velocity of 0.05m/s. Lower relative activity has been associated with cognitive demands of a task and reported lowered in neurological disease [Gulde, 2017b] and ageing [Gulde, 2017a]. Mean peak velocity is the average velocity of local velocity maxima with a minimum prominence of 0.05m/s. Reduced velocities have been reported in neurological disease [Baer, 2023; Gulde, 2017b; Huang, 2024; Reyes-Guzmán, 2014; Schwarz, 2022]. The number of velocity peaks is the number of velocity peaks with a minimum prominence of 0.05m/s in relation to the covered path length. Often referred to as a measure of movement smoothness [Gulde, 2018c; Huang, 2024; Pau, 2023; Reyes-Guzmán, 2014; Schwarz, 2022], it can also be interpreted as a measure of movement amplitudes. The velocity-acceleration peaks ratio is the number of velocity peaks with a minimum prominence of 0.05m/s divided by the number of acceleration peaks with a minimum prominence of 0.25m/s². Lower values derived from a higher number of or less synchronized (latent) acceleration curves to generate a movement and can be taken as a measure of movement smoothness; similar metrics proved to be sensitive in neurological disease [Baer, 2023; Gulde, 2023; Gulde, 2024; Gulde, 2025; Pau, 2023] and ageing [Schmidle, 2022]. Bimanual cooperation is the relative time in which both hands were exceeding velocities of 0.05m/s and a measure of bimanual performance, with higher values indicating more parallel work [Gulde, 2017a; Gulde, 2019]. The bimanual quotient is the absolute difference between the path lengths of the hands divided by its average. This quotient has been adapted from former studies [Gulde, 2017a; Gulde, 2019] and higher values indicate a lateralized amount of work, which can be task- or person-dependent. Such laterality has been observed not only in laboratory settings [Gulde, 2017a; Gulde, 2019], but also in a variety of wearable-based studies, i.a., in neurological disease [Geed, 2023; Gulde, 2024; Lee, 2024; Liu, 2025; Lohse, 2025; Porta, 2022]. Hand distance is the average of the mean Euclidean distance between both hands [m]. Higher values indicate that work is less centered and hands work further away from

each, which can be based on different tasks or only one task being carried out in the periphery (e.g., one hand resting on the kitchen plate near the body and the other far reaching).

The ADL component score represents an overall measure of the ADL kinematics. It was derived as the component score of a 1-dimensional confirmatory principal component analysis (varimax rotation; Eigenvalue 3.50, 0.39 explained variance) of the individual averaged z-scores of the participants. The parameter loadings were: TD -0.79, PL -0.21, RA 0.67, MP 0.77, NP -0.81, VAPR 0.62, BC 0.81, BQ 0.26, DIST – 0.19. It was thought to give a general performance metric with higher values indicating better performance.

Statistical analysis

Data were analyzed using three different approaches. First, age was correlated with capacity tests and ADL kinematics using 3rd degree polynomials. This allowed to identify most and least prone dimensions of capacity and functioning. Second, the relative frequency of individuals to show capacity (ratio of 7 tests) or performance (ratio of 9 metrics) worse than the 95% confidence interval of persons ≤ 40a of age (n = 33, representing 35% of the sample; the upper-limit of age was chosen based on maximum reported grip strength before decline [Huemer, 2023]) was calculated over the age span of the sample (year-wise if possible). The resulting curves were smoothed using a 10a loess algorithm, closing potential year-gaps. Using moving 30a linear regressions, the respective time-points (i.e., age) at which deterioration became significant were identified. Third, as the main analysis, capacity was set against ADL (the ADL performance score). Two linear regressions were laid into the data clouds and shifted to maximize the absolute difference between their regression coefficients. If the resulting solution explained ≤ 5% variance, a single linear regression was applied instead. This allowed to identify the respective capacity (where the regressions touched, if applicable), at which the association between capacity and ADL performance change (e.g., leaving the submaximal domain). This approach is a segmented regression analysis with an adjusted optimization target. Our approach targeted maximum differences as we anticipated areas of zero-association, which would not fit an approach that maximizes explained variance as segmented analyses aim to achieve.

Results

The 3rd degree polynomial regressions showed age-effects for almost all tested dimensions (Table 2). From the capacity tests, BB, GRIP, and TUG reacted strongest to ageing, while RT and TAP still showed strong coefficients. iADL performance showed weaker reactions to age, with the strongest associations seen in NP and ADL. Age against capacity and age against iADL performance are illustrated in Fig. 3 and Fig. 4.

Table 2
Age-association (3rd degree polynomial regression) of capacity and iADL performance outcomes.

Class	Abbrev.	R^2	p
Capacity	6CIT	0.01	0.383
	2PDT	0.22	< 0.001
	BB	0.55	< 0.001
	GRIP	0.49	< 0.001
	TUG	0.55	< 0.001
	TAP	0.35	< 0.001
	RT	0.33	< 0.001
iADL performance	TD	0.21	< 0.001
	PL	0.04	0.053
	RA	0.12	< 0.001
	MP	0.16	< 0.001
	NP	0.30	< 0.001
	VAPR	0.11	< 0.001
	BC	0.17	< 0.001
	BQ	0.04	0.061
	DIST	0.06	0.015
	ADL	0.22	< 0.001

For comprehensiveness, Fig. 5 shows the relationship between the capacity measures. Except 6CIT (|r|=0.002–0.11) and 2PDT (|r|=0.18–0.35), all measures revealed at least moderate linear associations (|r|=0.35–0.71).

Figure 6 shows the relative frequency of occurrences of low capacity or low kinematic iADL performance. For capacity, moving linear regressions with a 30a window size showed p-values below 0.10 starting at the age-window of 35 to 65a (center at 50a), p-values were constantly below 0.05 starting at the age-window of 45 tot 75a (center at 60a). For iADL performance, p-values were below 0.10 starting at the age-window of 43 to 73a (one p of 0.129 at 44 to 74a; center 58a) and p-values were below 0.05 starting at the age-window of 47 to 77a (one p of 0.057 at 59 to 89a; center 62a). Occurrence rates crossed the 95% confidence band of participants ≤ 40a at the transition from 59 to 60a (capacity) and at the transition from 71 to 72a (iADL performance).

As seen in Fig. 7, and according to the adjusted segmented regression analysis, not all capacity tests were strongly associated with the iADL performance score or showed a transition point at which the association changed. 6CIT showed an R^2 of 0.04 at a trend-level of $p = 0.062$. 2PDT showed no significant association with $R^2<0.01$ and a p-value of 0.456. Further, RT had an R^2 of 0.02 and a p-value of 0.183. All other capacity tests showed significant associations with transitions as listed in Table 3. For BB, individuals with more than 70.5 transferred blocks per minute did not further profit from higher capacity. Grip strengths of more than 46.2kg for males and 30.5kg for females turned from benefit to statistical impediment. TUG times above 5.7s (10.6/min) were predictive for performance, while higher capacity was not. TAP rates of below 5.3Hz were associated with strong changes in performance, while higher rates only showed a trend of being further beneficial. Before the age of 55a, participants tended to improve performance with advancing age, while after the age of 55a, the direction turned.

Table 3
Total and first and second regression R^2s and p-values as well as the transition point.

Metric	R^2 total	p total	R^2 first	p first (n)	R^2 second	p second (n)	Transition point
BB	0.14	< 0.001	0.27	< 0.001 (50)	< 0.01	0.771 (45)	70.5/min
GRIP	0.19	< 0.001	0.19	< 0.001 (75)	0.21	0.040 (20)	0.7 (m: 46.2kg / f: 30.5kg)
TUG	0.11	0.001	0.38	< 0.001 (26)	< 0.01	0.494 (69)	10.6/min (5.7s)
TAP	0.11	0.001	0.39	0.005 (18)	0.04	0.077 (77)	5.3Hz
Age	0.28	< 0.001	0.23	< 0.001 (46)	0.33	< 0.001 (49)	55a

Discussion

Findings summary

In this study, we cross-sectionally assessed sensorimotor and cognitive capacity of 95 healthy adults between 18 and 93a of age and examined its relationship with kinematic iADL performance. Strength, functional mobility, and dexterity reacted the strongest to ageing. Speed (motor and information processing speeds) and tactile resolution also reacted meaningfully to advancing age, while a short test of memory function showed no decline. iADL performance revealed an inverted U-curve, with improvements until the mid-fifties with a following decline. Both capacity and iADL performance revealed steep inclines of underperformance occurrences with ages passing the 50s (capacity) and 60s (performance). Memory function, tactile resolution, and information processing speed showed no associations with iADL performance, while the other capacity measures did. Capacity-performance associations were observed below but not above identified transition points (except for strength).

Capacity

As stated, not all capacity measures reacted to ageing. This could be due to a bottom effect of the 6CIT or to confounders like testing distress or preventive memory training in advanced age. Further, the 6CIT mixes different aspects like temporal orientation or working memory with low item difficulties. In accordance with literature, reaction times rather showed a linear association with age [Fozard, 1994; Zhang, 2026], while dexterity, functional ambulation, and grip strength revealed an acceleration of decline [Huemer, 2023; Meulemans, 2025]; in grip strength after an increase until mid-age [Huemer, 2023]. Strength also appeared to reveal the highest variance, emphasizing that observed strength is the combination of training and, in this case, age-related decline [Jones, 2022; Lemmer, 2007]. The remarkably strong decline of dexterity could be related to age-related changes of muscle physiology that would also explain the strong relationship between dexterity and strength [Jones, 2022]. It is highly interesting that strength (including functional ambulation) reacted stronger to ageing than speed (motor speed (tapping) and information processing speed (reaction times)). This speaks towards a more robust neurological status (including the weaker association of tactile resolution and the missing relationship of memory function - similar findings on memory function have been previously reported [Hooyman, 2020]) than muscular capacity, as especially tapping has been shown to be a good indicator of neural conductivity [Gulde, 2022]. However, one has to keep in mind that memory function alone would not be the most sensitive indicator of an age-related brain state [Fjell, 2025]. The steep increase of occurrences of low-capacity outliers further indicates that when entering a chronological age, where accelerated decline appears (on population level) [Meulemans, 2025], individual biographies become more important. The different age-points of capacity and iADL performance further underline that declining capacity does not instantly lead to iADL not being submaximal anymore [Schwerz de Lucena, 2021], which can be a risk to not counteract as early as possible. The higher prevalence of outliers in advancing age further suggests that when accumulating sensorimotor capacity declines, compensation in iADL performance can become limited. Therefore, even well-performing systems could be not as robust as they appear and strategies to develop or maintain higher capacities as needed seem imperative.

iADL performance

The iADL performance followed a U-curve, indicating that performance improves during younger adulthood. This could be explained by experience gains [Gulde, 2019] or even by capacity (strength, dexterity, and motor speed tend to increase during that time). Notably, the performance of the oldest participants was comparable to the performance of the youngest participants in our sample – which is partially in line with prior findings [Gulde, 2017a; Gulde, 2019]. However, the occurrence of low-performance outliers drastically increased in advanced age, indicating that preserving performance is strongly linked to individual biographies and that compensation of impaired functioning is likely. The age at which these occurrences accumulate (in the sample) is interestingly (approx.) the age at which the highest performances were observed. This could be explained by individuals being able to keep their capacity levels in a range, where iADL remain submaximal, and at the same time accumulate experience (incl. transfer from other complex, multi-step tasks [Ferguson, 2021]). A post-hoc analysis revealed that

the minimum capacity of the best-performing 5% (iADL) was as follows: GRIP – 0.35, BB 65.5/min, TAP 6.25Hz, TUG 11/min (5.44s), 2PDT 3mm, 6CIT 2, and an age between 42a and 58a. These values are, except GRIP and TAP, very close to the identified transition points, further underlining the idea of preserving capacity and accumulating experience. The identification of transition points showed that above given capacities, there was no further benefit for iADL performance with increasing capacity. The only exception was strength (GRIP), where high values beyond the transition point were significantly associated with a decline of performance. It is unlikely to be a pure age artifact (very young adults with great strength and low iADL performance), as TUG and BB showed similarly strong age-relations. Soft-tissue inhibition or worse body part size to object size ratios (“huge fingers”) was examined and ruled out (body height vs. GRIP (R^2=0.13, $p < 0.05$) was similarly to body height vs. TUG (R^2=0.12, $p < 0.05$) and BMI vs. GRIP was non-significant (R^2=0.05, $p > 0.10$)). One could speculate that this could be the consequence of motor unit remodeling (age and intensified resistance training) that could interfere with slow, precise movements as they are needed in iADL [Jones, 2021], but this is highly speculative [Martin, 2015; Smits-Engelsman, 2008]. The transition points appeared at relatively high capacity levels (especially for GRIP), indicating that iADL could be not as submaximal as they are commonly thought to be. Prior findings already emphasized the complexity and cognitive demands of iADL [Gulde, 2017b], perhaps the sensorimotor aspect should be added. However, given data suggests that declines in capacity can be compensated and, e.g., in the face of disease or emphasized age-related capacity declines, training iADL could potentially help to remain a certain amount of independence in daily life; though, it has to be kept in mind that just living everyday life is not training [Gulde, 2024; Schwerz de Lucena, 2021].

As illustrated in Fig. 4, most capacity tests correlated with each other. This can be expected as we covered a wide age range and most tests reacted to age. A post-hoc 1D confirmatory principal component analysis with the capacity tests revealed that all tests but 6CIT (loading of 0.04) and 2PDT (loading of -0.48) loaded strongly on the extracted component, with the order: TUG (loading of 0.88), BB (loading of 0.86), TAP (loading of 0.80), GRIP (loading of 0.74), and RT (loading of 0.70). This implies that in a sample without clear indications (e.g., arthrosis, dementia, or stroke), declines are relatively homogenous, making single-test screenings potentially feasible. Considering the transition point analysis, TUG and TAP would be good candidates, covering ambulation and upper-limb function with a speed emphasis (keeping the shared variance with RT, Fig. 5).

Limitations

One limitation is that we did not assess the education level of participants. However, as we targeted the association of capacity and age with iADL performance, this should not have played a strong role. Further, studies have shown that the education level rather dictates the intercept, but not the slope of ageing-related changes [Fjell, 2025], so, effects could most likely be negligible in the given (estimated) homogenous sample. Other limitations are in respect to the chosen assessments for memory function (6CIT) and tactile resolution (2PDT), which showed bottom effects. Given the resulting small variance and information loss at the bottom of the scales, subtle associations with iADL performance, ageing,

and other dimensions of capacity could have not been detected (if present). The chosen tests for cognitive capacity (6CIT and RT) did also not fully cover the domains of executive functions; this should be included in future studies (e.g., by a non-motor task like the PASAT). The chosen threshold for the outlier occurrence analysis interestingly turned out to be put in a suboptimal age range, when considering the iADL performance (best performers between 42 and 58a, threshold based on ≤ 40a). This might have led to high thresholds, not necessarily affecting the detected onset of decline but the reached frequencies (scaling). Further, the kinematic analysis did not include grip types that could have been of interest; however, different grips lead to different reaching strategies and therefore this information should be at least indirectly included [Gentilucci, 1991]. Considering the iADL score, it did only cover approx. 40% of the observed variance and therefore a large proportion of behavioral variance was not covered by the analyses. Lastly, the cross-sectional design neglects cultural influences, e.g., changes in education [Lynch, 2003] or healthy lifestyle education [Schermer, 2022] on a population level, in addition to a selection/survival bias in advanced age [Batljan, 2009; Banack, 2019; Bootsma-van der Wiel, 2002].

Conclusion

A non-linear relationship between sensorimotor and cognitive capacity, age, and iADL performance was observed. Capacity declines before iADL performance in the course of ageing, but subtle changes in iADL performance do also appear relatively early in age and in relation to identified capacity transition points. iADL likely benefited from experience, which could counteract capacity declines. Still, preservation of capacity beyond the transition points is indicative to allow high iADL performance through the lifespan.

Declarations

Author Contribution

Conceptualization: PG, JH.Methodology: PG, LS, SC, PV-F, VT, JH.Investigation: LS, SC, PV-F, VT.Data curation: LS, SC, PV-F, VT.Software, hardware preparation: PG, LS, SC, PV-F, VT.Analysis: PG, LS, JH.Writing: PG, LS, JH.Review, editing, approval: PG, LS, SC, PV-F, VT, JH.

Data Availability

Data are available under reasonable request from the corresponding author.

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Figures



Figure 1

TUM Living Lab with kitchen and optoelectronic motion capturing system (marked with green circles).

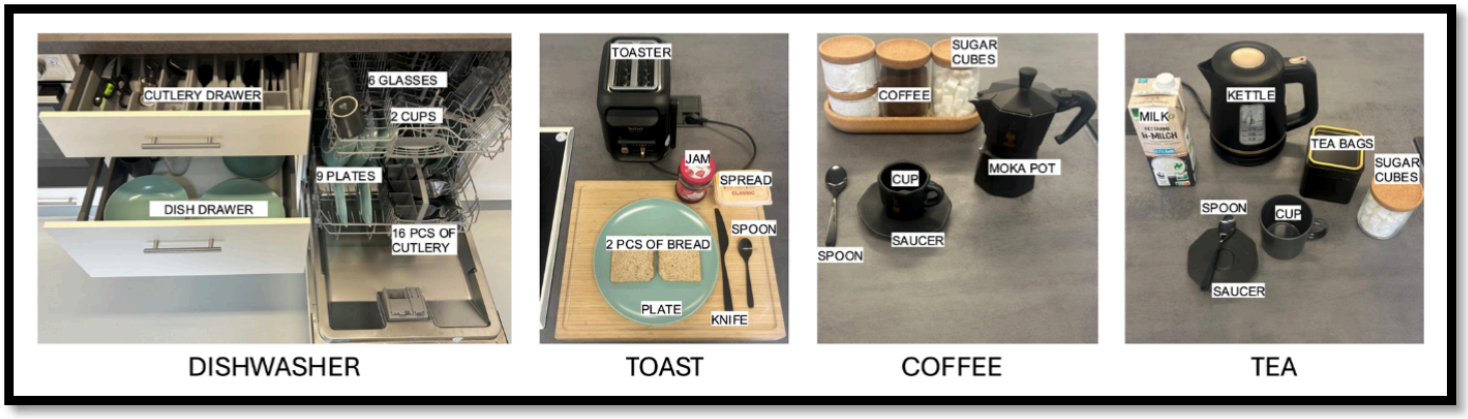


Figure 2

Set-up of the four iADL in the Living Lab; tea making, making coffee, preparing toast, emptying a dishwasher. Labels depict details, e.g., the number of plates of the dishwasher task.

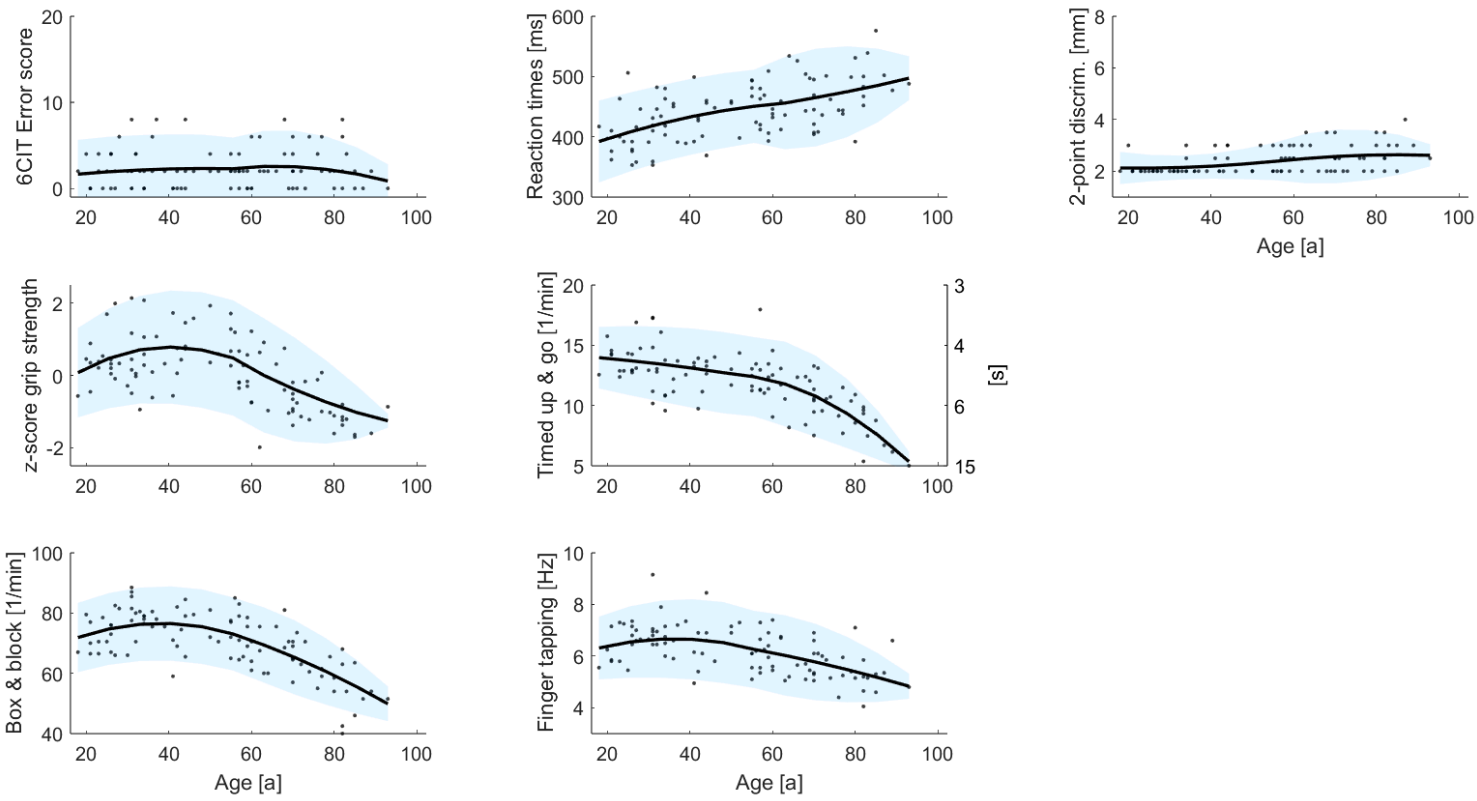


Figure 3

Capacity against age. The solid linear represents the mean with a window size of 10% of the age range (smoothed with a 10-point loess algorithm), the blue area is the 95% confidence interval (following the same processing).

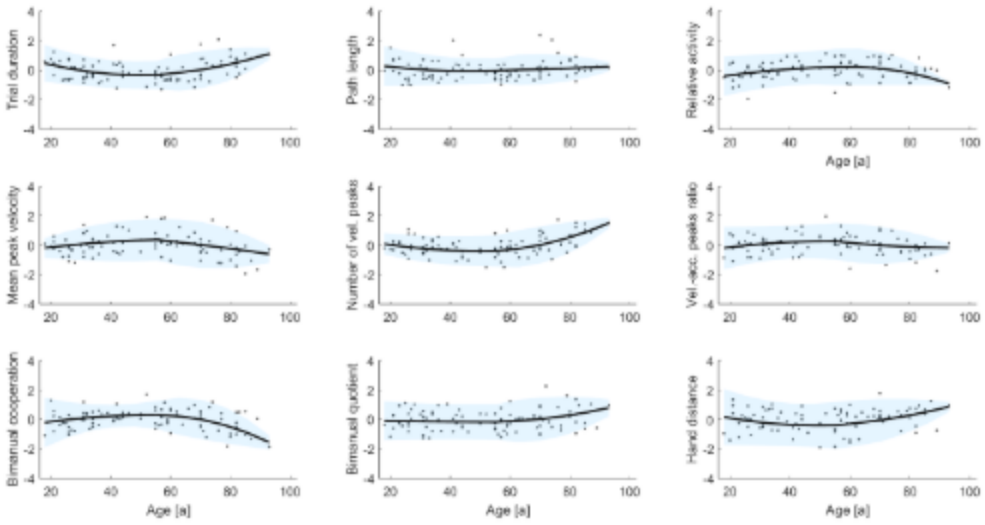


Figure 4

Performance against age. The solid linear represents the mean with a window size of 10% of the age range (smoothed with a 10-point loess algorithm), the blue area is the 95% confidence interval (following the same processing).

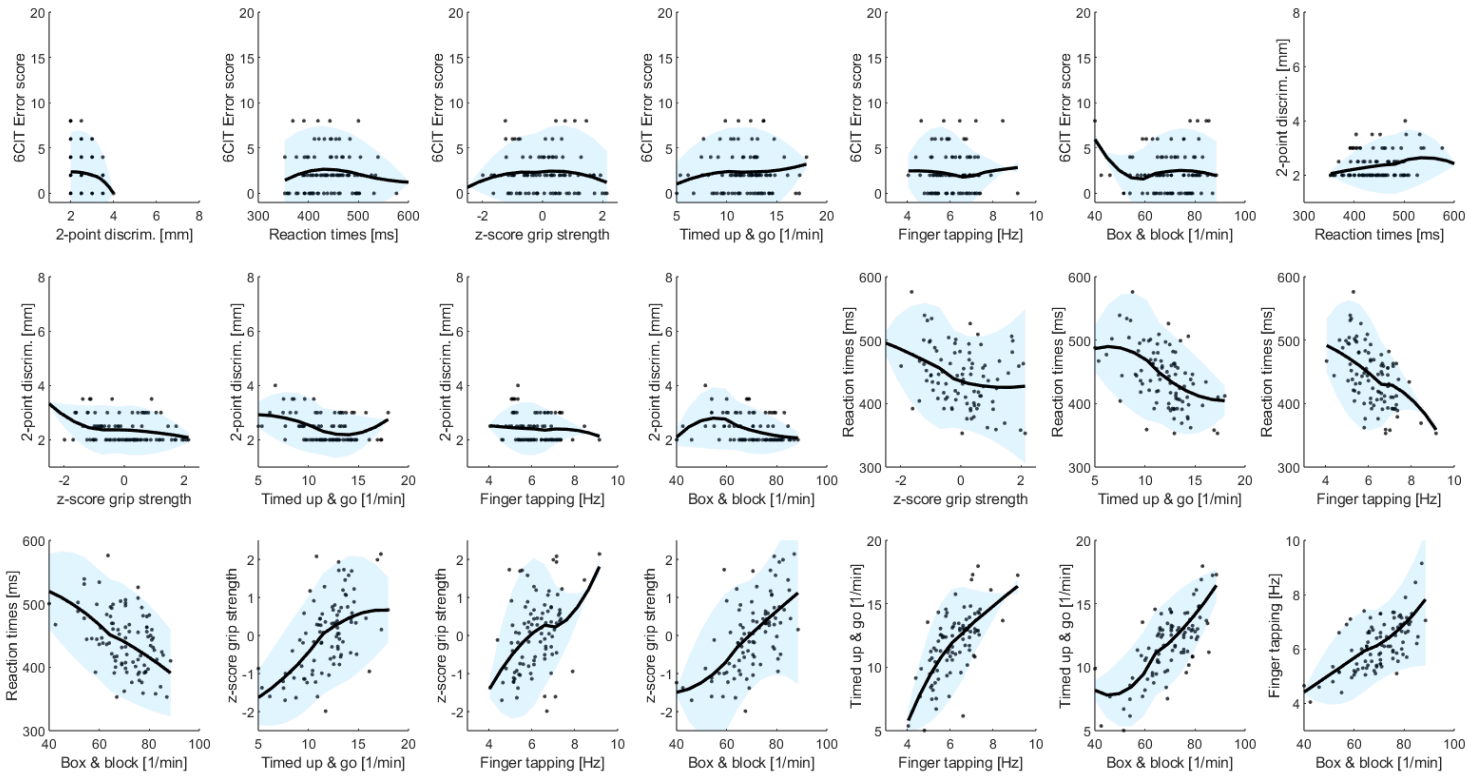


Figure 5

Association of capacity measures. The solid linear represents the mean with a window size of 10% of the range of the parameter of the x-axis (smoothed with a 10-point loess algorithm), the blue area is the 95%

confidence interval (following the same processing).

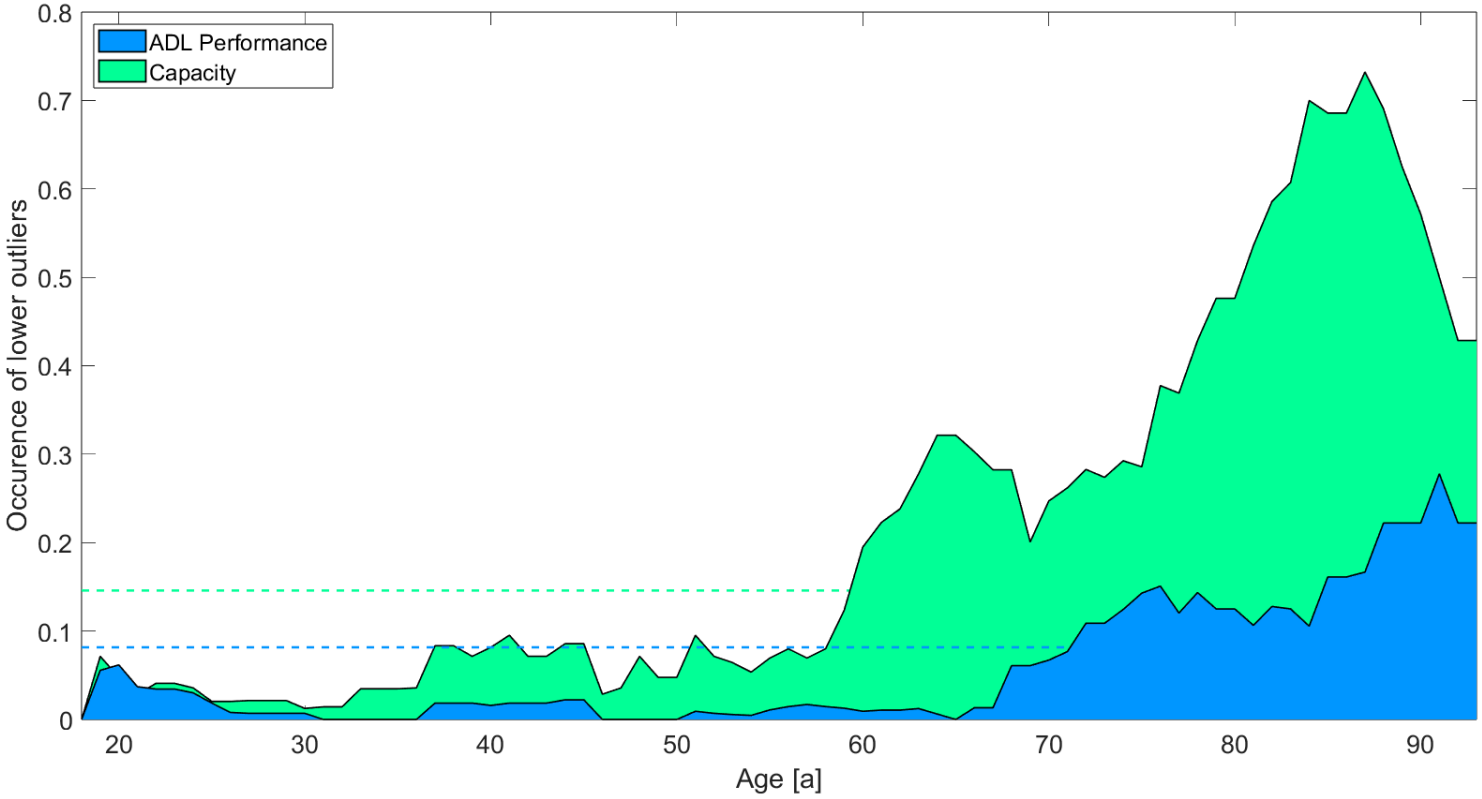


Figure 6

Relative frequency of low capacity (green, 7 tests) or iADL performance (blue, 9 metrics) (worse than the 95% confidence interval of participants ≤40a of age). The dotted lines denote the upper bounds of the 95% confidence interval of occurrences in participants ≤40a of age.

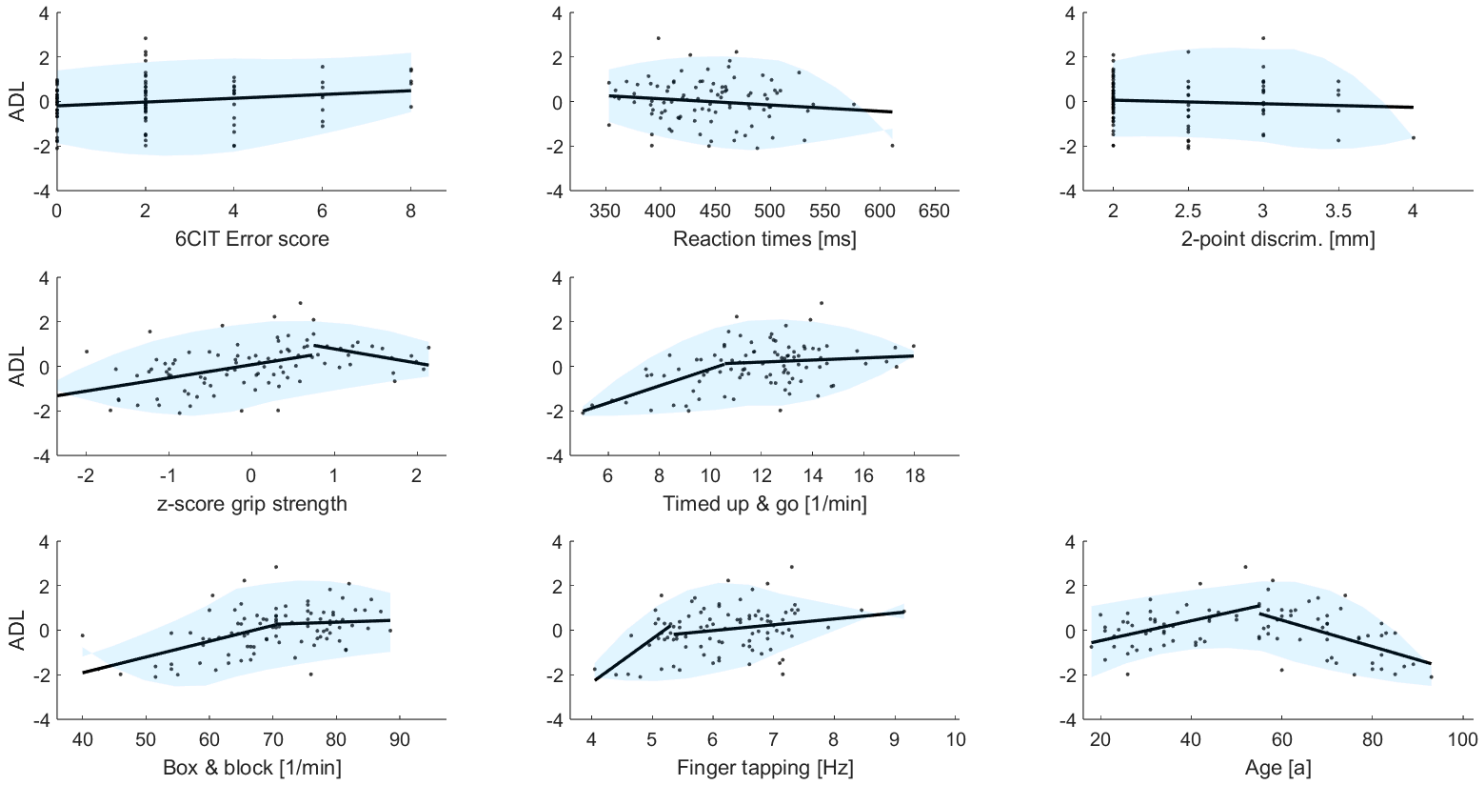


Figure 7

iADL performance score against capacity and age. Where more than 5% variance were explained, two linear regressions were set and optimized towards a maximum absolute correlation coefficient difference. The blue area represents the 95% confidence interval with a window size of 10% of the age range (smoothed with a 10-point loess algorithm).